

Studies of multi-pass Beam Breakup at Jefferson Lab

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Jefferson Lab

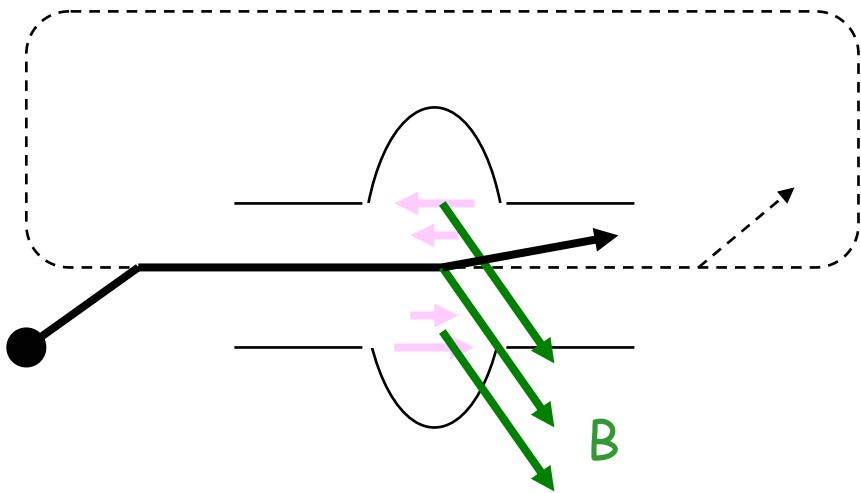
Outline

- Simplified theoretical model of multi-pass BBU
- Overview of BBU codes
- Experimental studies of BBU at JLAB FEL
 - BBU observations
 - Beam Transfer Function (BTF) measurements with recirculated beam
 - BBU suppression experiments at JLAB FEL
 - HOM polarization measurements at JLAB FEL
- BBU suppression techniques in perspective of large-scale machines

Simplified theoretical model of multi-pass BBU

HOM \Leftrightarrow DIPOLE HOMs

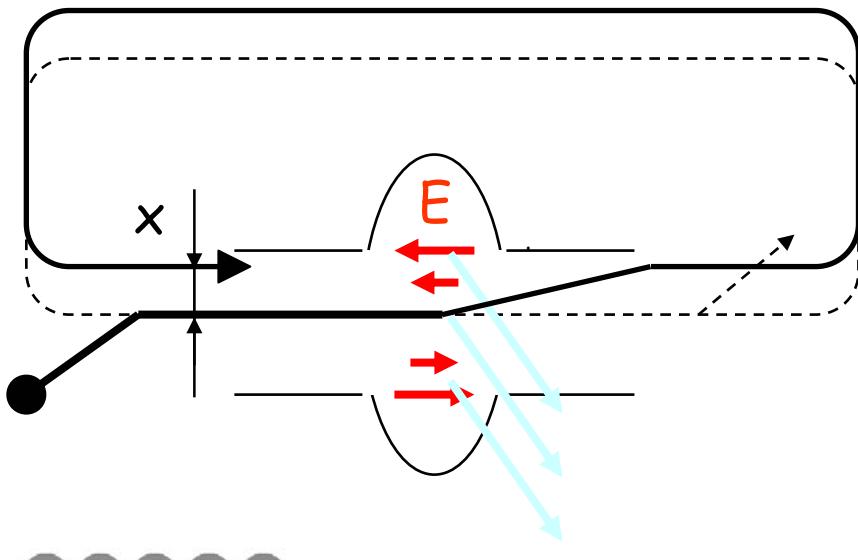
Energy transfer from the beam to HOM



1st PASS

$$V(r = a) = V_a \cos(\phi) = \int E_z^{\max}(r = a) dz \cos(\phi)$$

$$x' = \frac{V_{\perp}}{V_b} = -\frac{\frac{cV_a}{\omega a} \sin(\phi)}{V_b}$$



2nd PASS

$$x = m_{12} x'$$

$$\Delta U = -qV_a \cos(\phi + \omega T_r) \frac{x}{a}$$

$$V_q = qa^2 \frac{\omega}{2} \left(\frac{\omega}{c} \right)^2 \left(\frac{R}{Q} \right) \frac{x}{a}$$

BBU threshold equation

The threshold corresponds to equilibrium between deposited and dissipated power.

At the equilibrium, the stored HOM energy does not change ($dU/dt=0$)

The formula yields two regions:

$m_{12}\sin(\omega T_r) < 0$ – unstable

$m_{12}\sin(\omega T_r) > 0$ – “pseudo” -stable

(Thorough analysis by
J. Bisognano, G. Krafft,
S. Laubach, 1987, B. Yunn, 1991
Hoffstaetter, Bazarov, 2004)

$$\dot{U}_{cav} = \dot{U}_{beam} - P_c = \langle \Delta U_{in} + \Delta U_{out} \rangle \cdot f_b - P_c$$

$$P_c = \frac{V_a^2}{(\omega/c)^2 a^2 \left(\frac{R}{Q} \right) Q_L}$$

$$\frac{dU}{dt} = -\frac{V_a^2}{a^2} \left(I_b \frac{m_{12}}{V_b} \frac{c}{\omega} \frac{\sin(\omega T_r)}{2} + \frac{1}{(\omega/c)^2 \left(\frac{R}{Q} \right) Q_L} \right)$$

$$I_{th} = -\frac{2V_b}{(\omega/c) \left(\frac{R}{Q} \right) Q_L m_{12} \sin(\omega T_r)}$$

Two dimensional case (single mode)

Single mode, two-pass recirculator,
arbitrary $m(4 \times 4)$, arbitrary mode polarization α

$$x \rightarrow \vec{d} \cdot \vec{n} = x \cos(\alpha) + y \sin(\alpha)$$

$$I_{th} = -\frac{2V_b}{(\omega/c)\left(\frac{R}{Q}\right)Q_L m^* \sin(\omega T_r)}$$

$$m^* = m_{12} \cos^2(\alpha) + (m_{14} + m_{32}) \sin(\alpha) \cos(\alpha) + m_{34} \sin^2(\alpha)$$

(Pozdeyev, 2004)

Two dimensional case (degenerate modes)

Two degenerate dipole modes polarized in x and y.

$$M(4 \times 4) = \begin{bmatrix} 0 & A \\ B & 0 \end{bmatrix}$$

for $M_{14} M_{32} > 0$

$M_{14} M_{32} < 0$

$$I_{th} = \frac{2E\omega \exp\left(-\frac{\omega t_\tau}{2Q}\right)}{ec\left(\frac{Z''T^2}{Q}\right)Q\sqrt{M_{14} M_{32}}|\sin \omega t_\tau|}$$

$$I_{th} = \frac{2E\omega \exp\left(-\frac{\omega t_\tau}{2Q}\right)}{ec\left(\frac{Z''T^2}{Q}\right)Q\sqrt{-M_{14} M_{32}}|\cos \omega t_\tau|}$$

(B. Yunn, 2005)

Voltage evolution above and below I_{th}

$$\frac{V_a^2}{a^2} = \omega \left(\frac{\omega}{c} \right)^2 \left(\frac{R}{Q} \right) U$$

$$\frac{dU}{U} = -dt \frac{\omega}{Q_L} \frac{I_{th} - I}{I_{th}}$$

$$U = U_0 \exp \left(-t \frac{\omega}{Q_L} \frac{I_{th} - I_b}{I_{th}} \right)$$

$$V = V_0 \exp \left(-t \frac{\omega}{2Q_L} \frac{I_{th} - I_b}{I_{th}} \right)$$

The system HOM+beam can be described by the effective quality factor:

$$Q_{eff} = Q_L \frac{I_{th}}{I_{th} - I} \quad \Leftrightarrow \quad \tau_{eff} = \tau_0 \frac{I_{th}}{I_{th} - I}$$

Overview of BBU codes

Multi-pass BBU codes

Multi-pass BBU code can be separated in two groups according to their algorithm: **TRACKING** or **EIGENVALUE**

Name	TDBBU	New Code	bi	BBU-R	MATBBU
Developer Lab	JLab	JLab	Cornell U.	JAERI	JLab
Algorithm	tracking	tracking	tracking	tracking	eigenvalue
# Dimensions	2D	2D	2D	1D	1D
# Recirculation	unlimited	unlimited	unlimited	2	unlimited
Single pass	yes	yes	yes & no	?	no
Input	opt. elements	opt. elements	matrices	?	opt. elements
Exec. speed*	slow	fast	fast	?	intermediate
Programming Language	Fortran/C	C++/Java	C++	C	Fortran/C

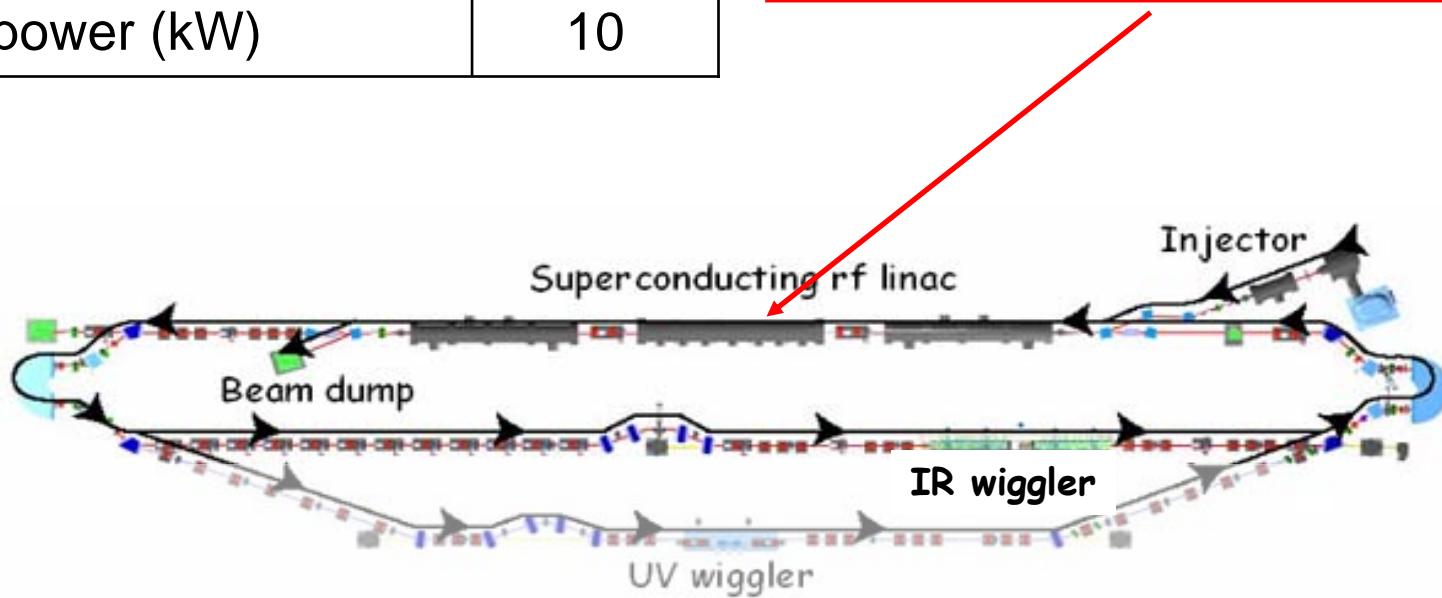
* - no thorough, quantitative comparison has been performed.

Experimental studies of BBU at JLAB FEL

JLab FEL Upgrade

Energy(MeV)	80-200
Charge per bunch (pC)	135
Bunch rep.rate (MHz)	4-75
Average current (mA)	10
Laser power (kW)	10

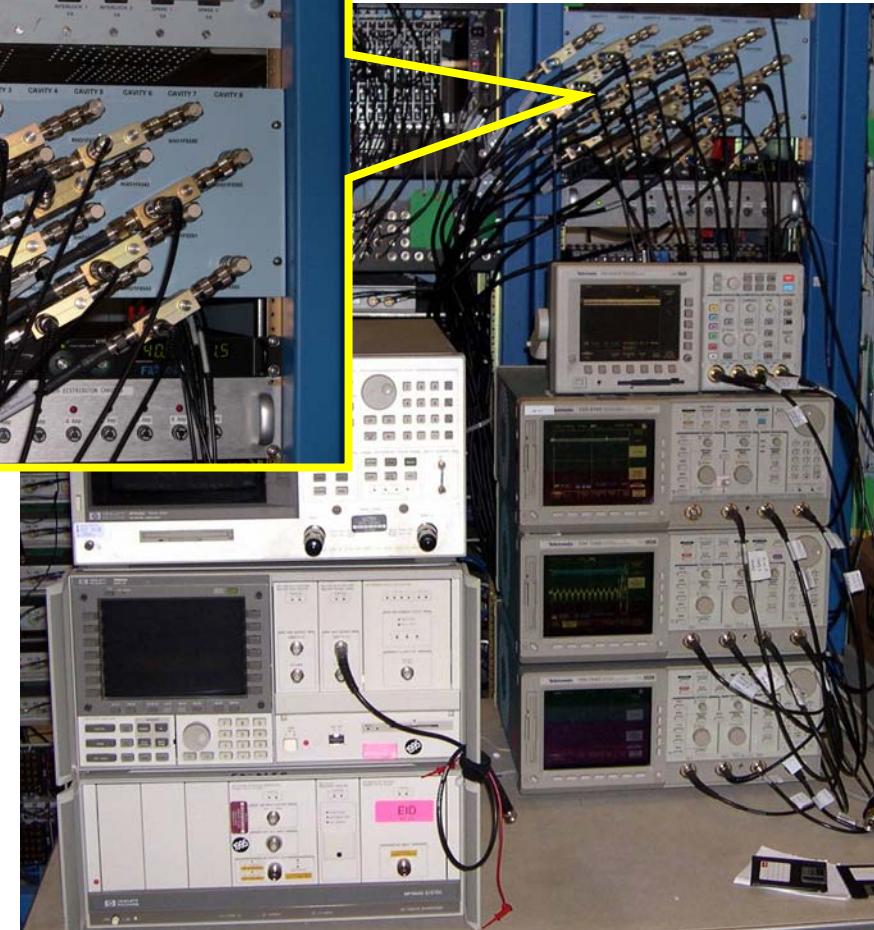
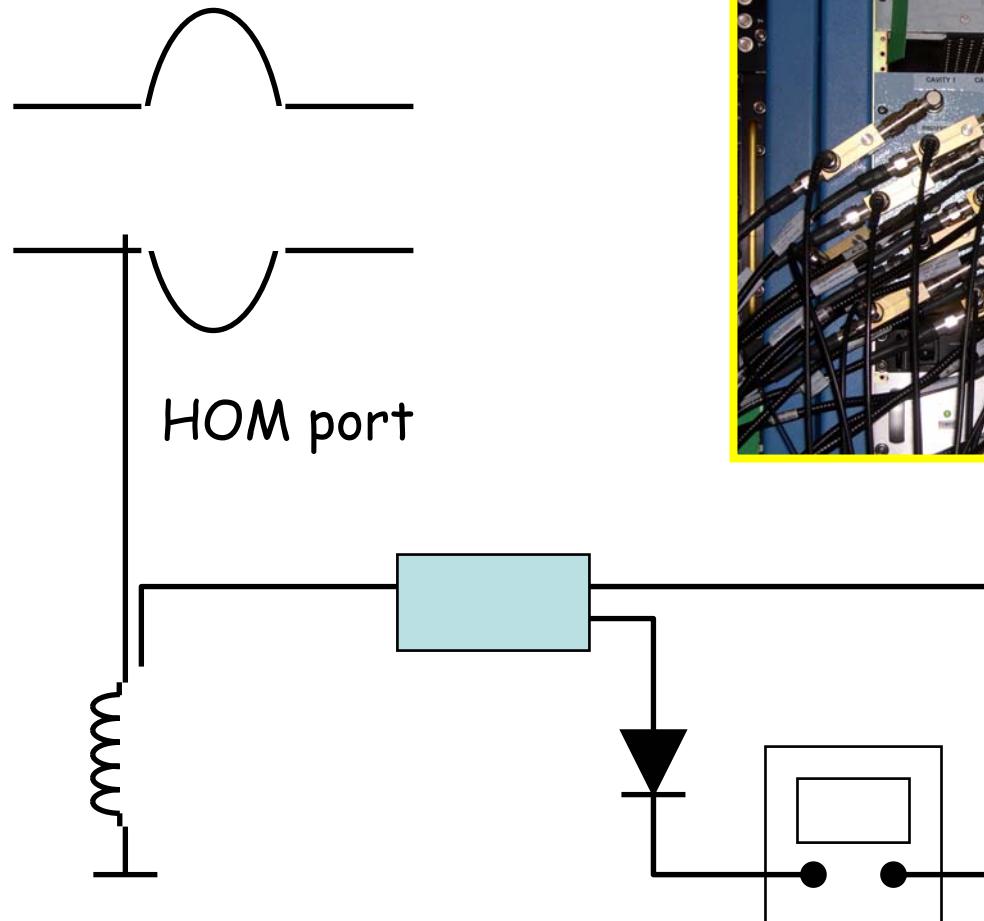
Cavities of Zone 3 have higher accel. gradient than Zone 2,4. The Q of dipole HOMs is also higher. HOMs of Zone 3 impose BBU limit.



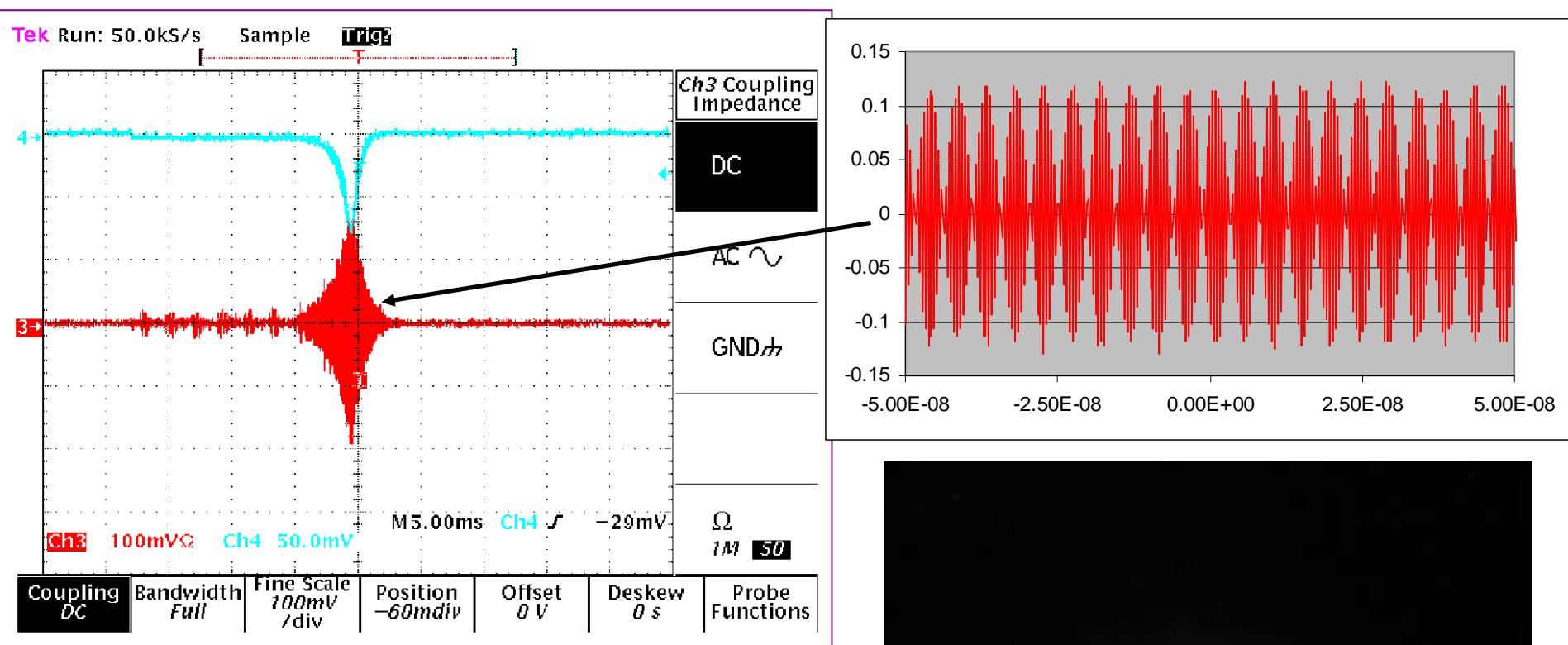
Direct observation of the BBU threshold

Schottky diodes were used to measure HOM power from the HOM ports.

(K. Jordan)

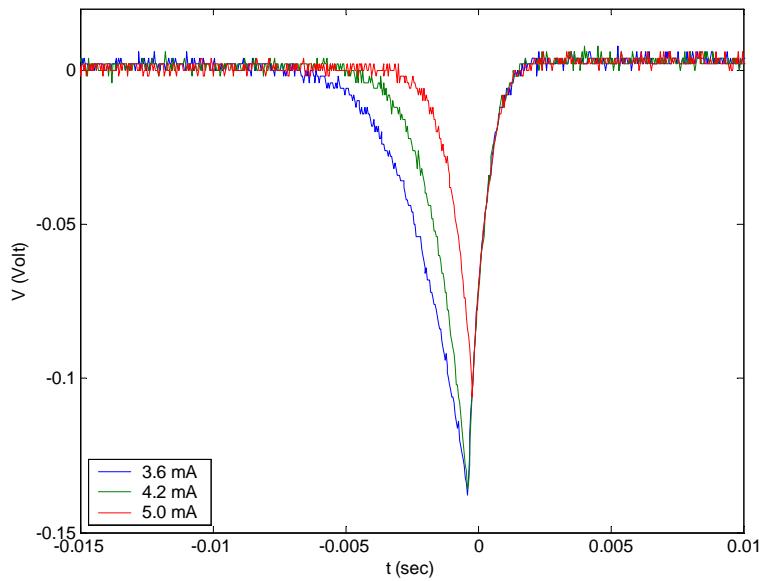


Direct observation of the BBU threshold

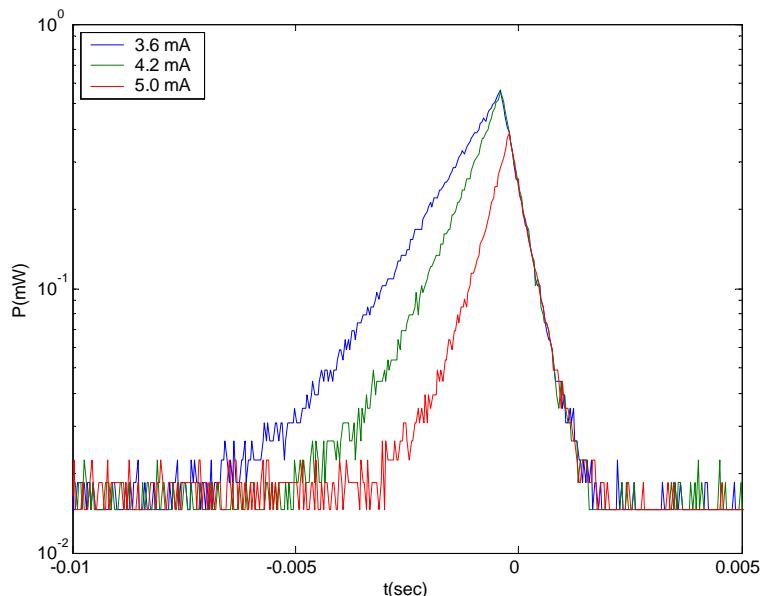


Cav 7, $F_{hom} = 2106$ MHz, $I_{th} = 2.7$ mA

Direct observation of the BBU threshold HOM voltage growth rate measurements

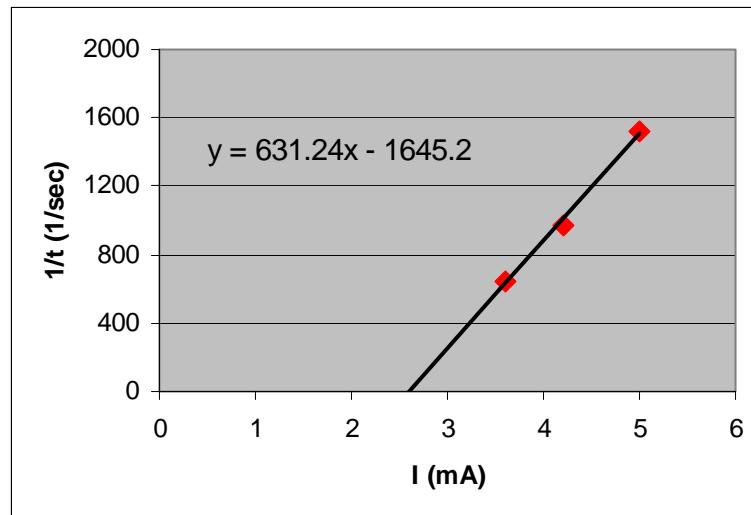


invert
+
adjust
+
log

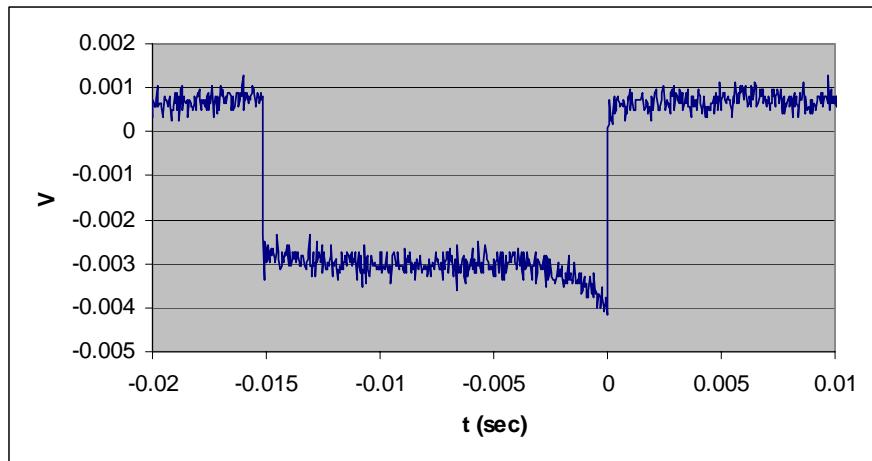


$$\tau_{eff} = \tau_0 \frac{I_{th}}{I_{th} - I}$$

Cav 7, $F_{hom}=2106$ MHz,
 $I_{th}=2.6$ mA



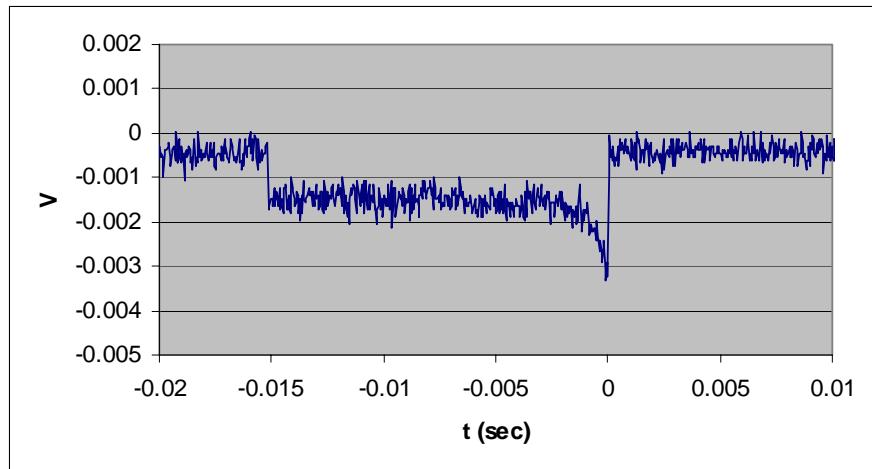
What about other HOMs?



$I=5\text{mA}$

Cav. 3, $F=1786.206$

BTF measurements: the HOM is very far from the threshold (BTF-predicted $I_{\text{th}}=34\text{ mA}$)



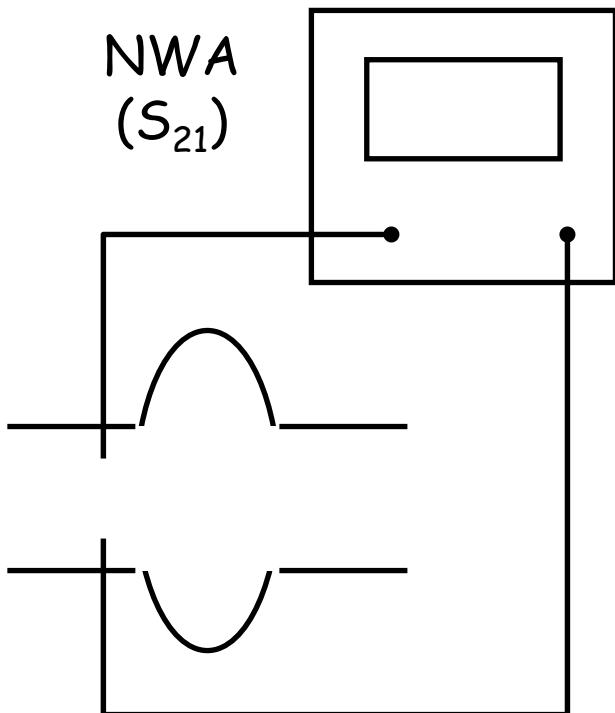
Cav. 8, $F=1881.481$

BTF measurements inconclusive.
Cross-talk prevented us from taking accurate BTF data.

We are not sure what causes this voltage rise

Beam Transfer Function (BTF) measurements

Measuring Q(I) for several beam current values and using the formula



$$Q_{eff} = Q_L \frac{I_{th}}{I_{th} - I}$$

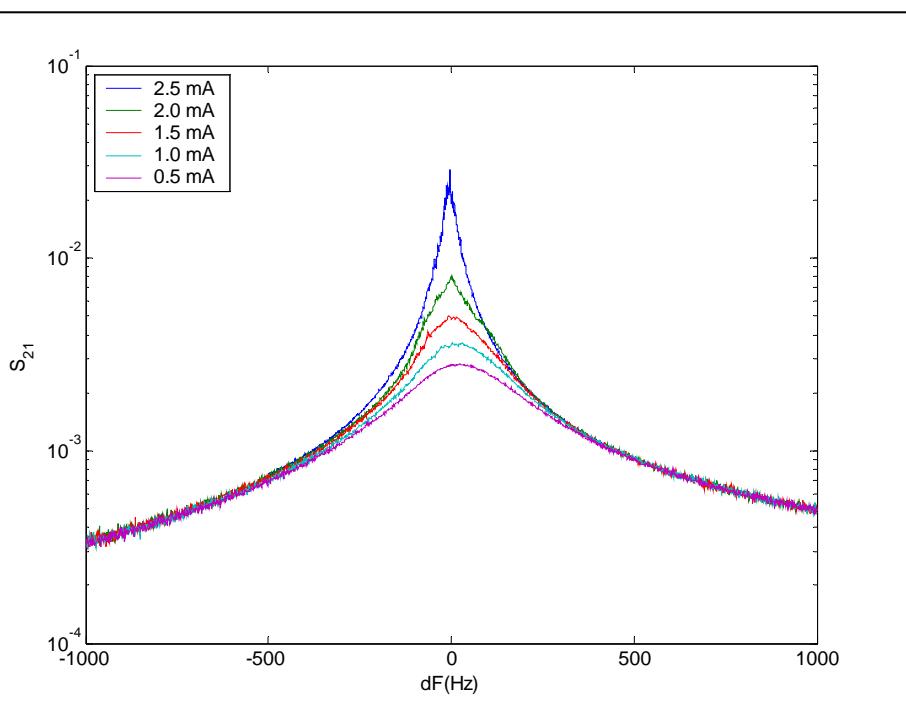
one can predict the BBU threshold below the threshold.

Port-to-port BTF:

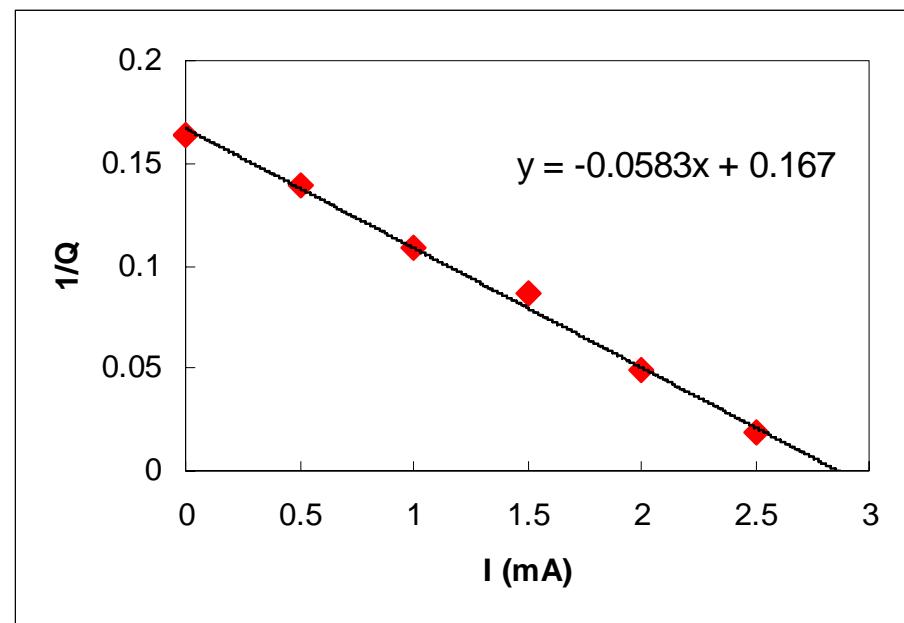
- +':
 - 1) stronger signal
 - 2) no need for RF amplifier
 - 3) no need for kicker
- ':
 - cross-talk can complicate Q-measurements

Beam Transfer Function (BTF) measurements

Cav 7, $F_{hom}=2106$ MHz



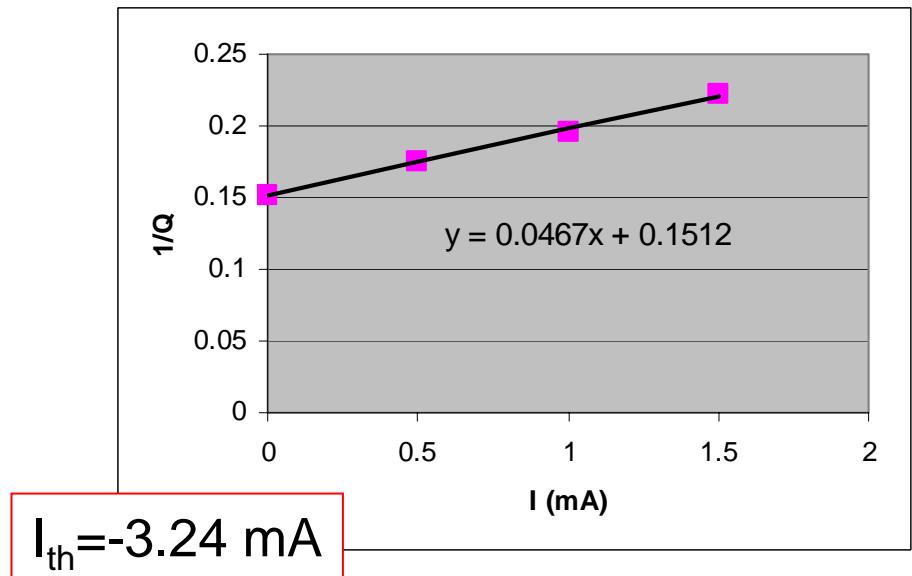
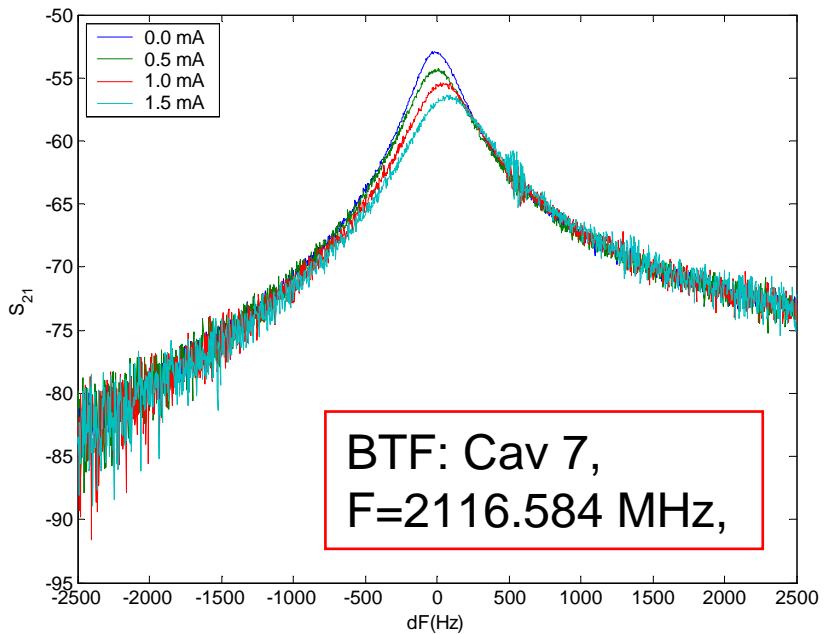
$$Q_{eff} = Q_L \frac{I_{th}}{I_{th} - I}$$



Projected threshold current is 2.9 mA

Beam Transfer Function (BTF) measurements in the “pseudo”-stable region ($m_{12}\sin(\omega T_r) > 0$)

$$Q_{eff} = Q_L \frac{I_{th}}{I_{th} - I} = Q_L \frac{-|I_{th}|}{-|I_{th}| - I} = Q_L \frac{|I_{th}|}{|I_{th}| + I}$$



For $m_{12}\sin(\omega T_r) > 0$, BBU still can happen at very high currents (~10A).

(J. Bisognano, G. Krafft, S. Laubach (1987), B. Yunn, 1991

Hoffstaetter, Bazarov (2004))

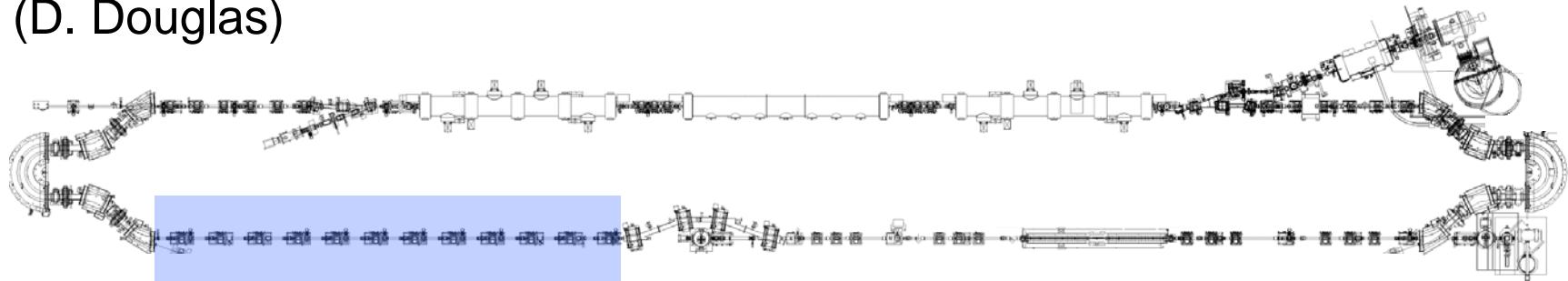
Summary of BBU threshold measurements, calculations, and simulations

Method	Threshold (mA)
Simplified formula	3.3
Simulations* (TDBBU, MATBBU, New Code)	2.5-3.1
Direct Measurement	2.7
Calculated from the instability growth rate	2.6
BTF	2.9

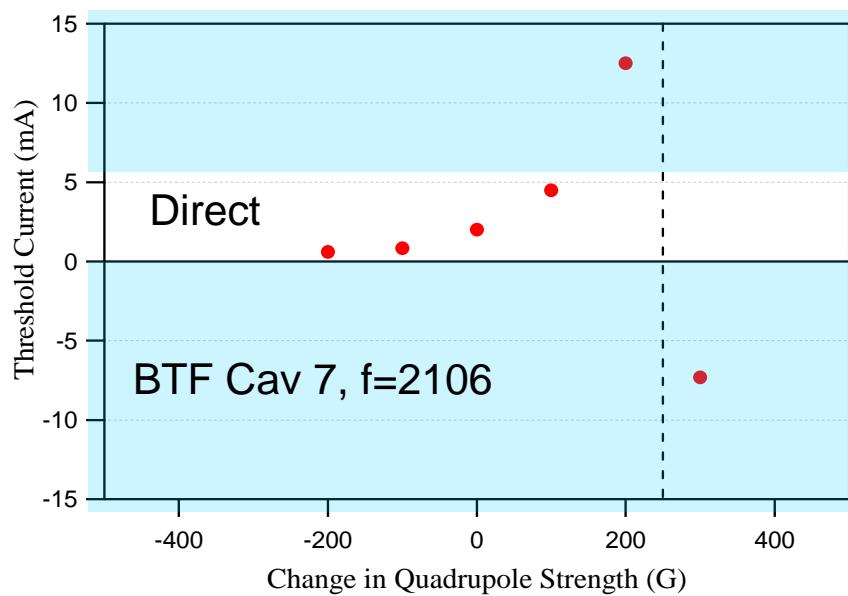
* - Dave Douglas' optics file (Nov.2004) with "All Save" quadrupole values

BBU suppression at the FEL: Point-to-Point focusing (Phase Trombone)

(D. Douglas)



Quadrupoles of the **blue** region
were adjusted to maximize I_{th}



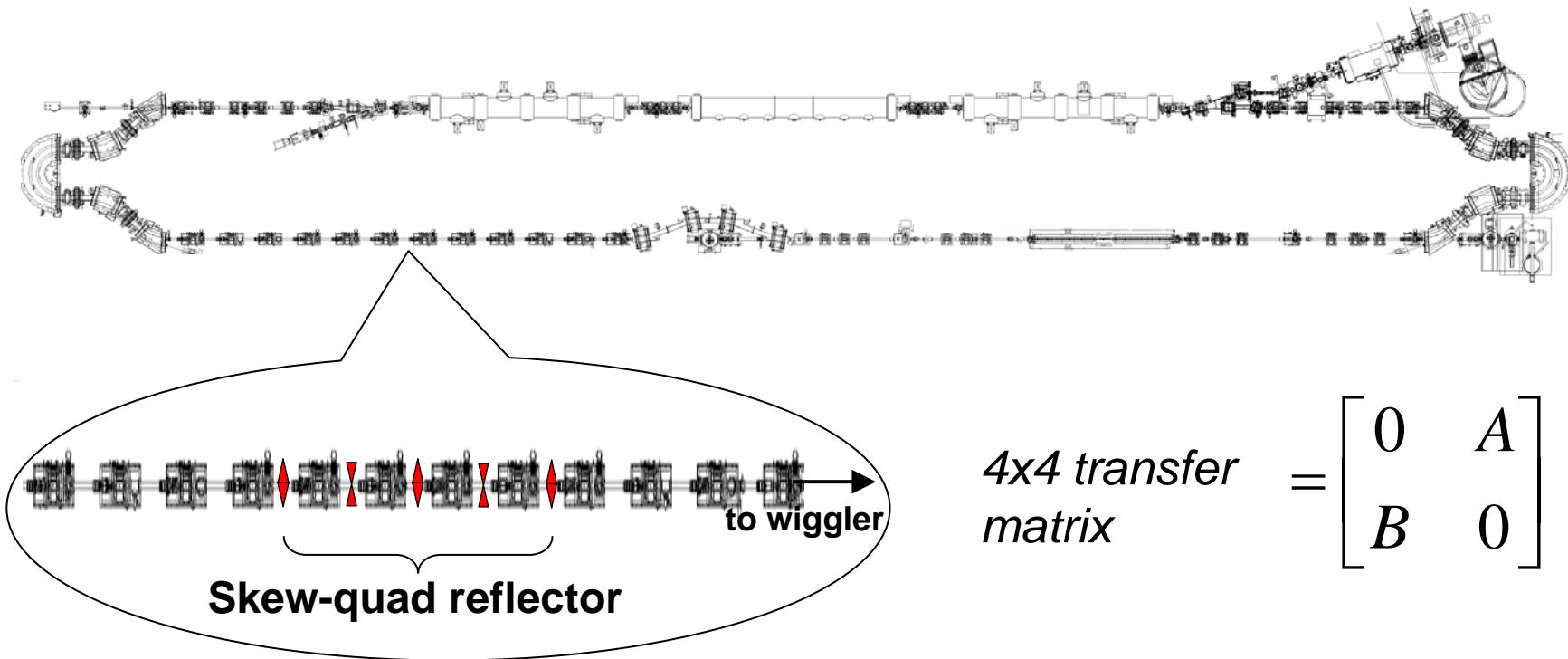
$$I_{th} = -\frac{2V_b}{(\omega/c)\left(\frac{R}{Q}\right)Q_L m_{34} \sin(\omega T_r)}$$

$$m_{34} \propto \sin(\psi) = \sin(n\pi + \delta) \approx (-1)^n \delta$$

Realistically, the threshold increase factor in the FEL is limited to 2 – 3.

BBU suppression at the FEL: Reflector

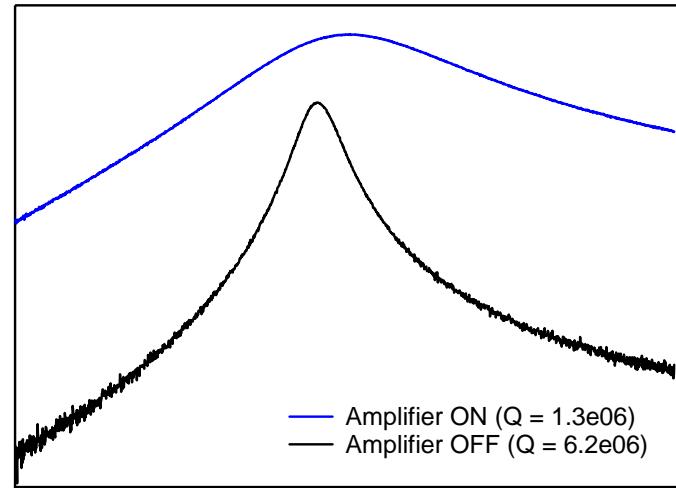
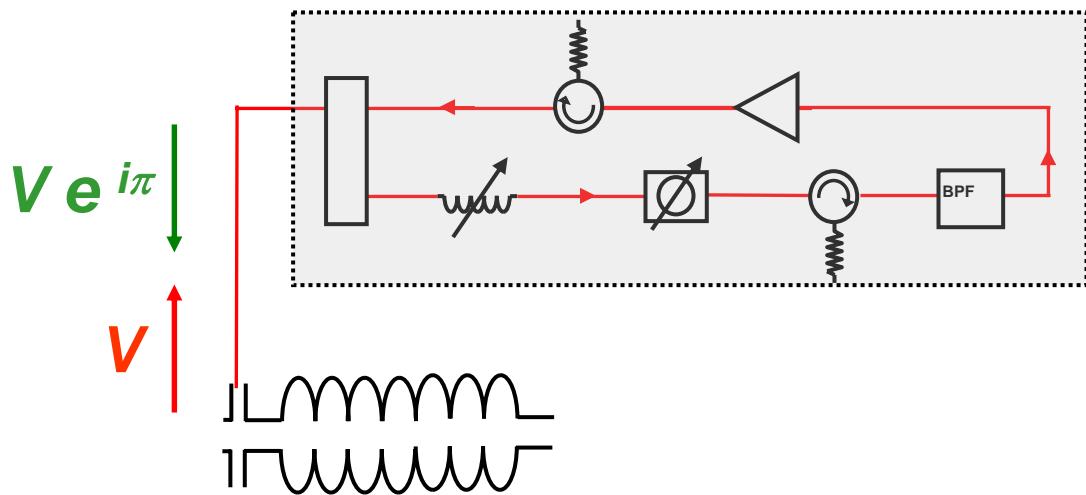
Idea: R. Rand, T. Smith (1980). Implemented: D. Douglas + FEL team (2004)



The BBU threshold was pushed above 8 mA and was limited by the injector.
For Cav 7, $f=2106$ HOM, I_{th} was increased from 2 mA \rightarrow 10 mA
(measured by the BTF technique)

BBU suppression at the FEL: Cavity Feedback

(Simrock, Pozdeyev, Tennant)



HOM resonance curve
with and without
feedback (no beam)

Suppression factors up to 20 were achieved for a short period of time.
Suppression factors of 5 to 10 were achieved reliably.

Summary of tested BBU suppression techniques

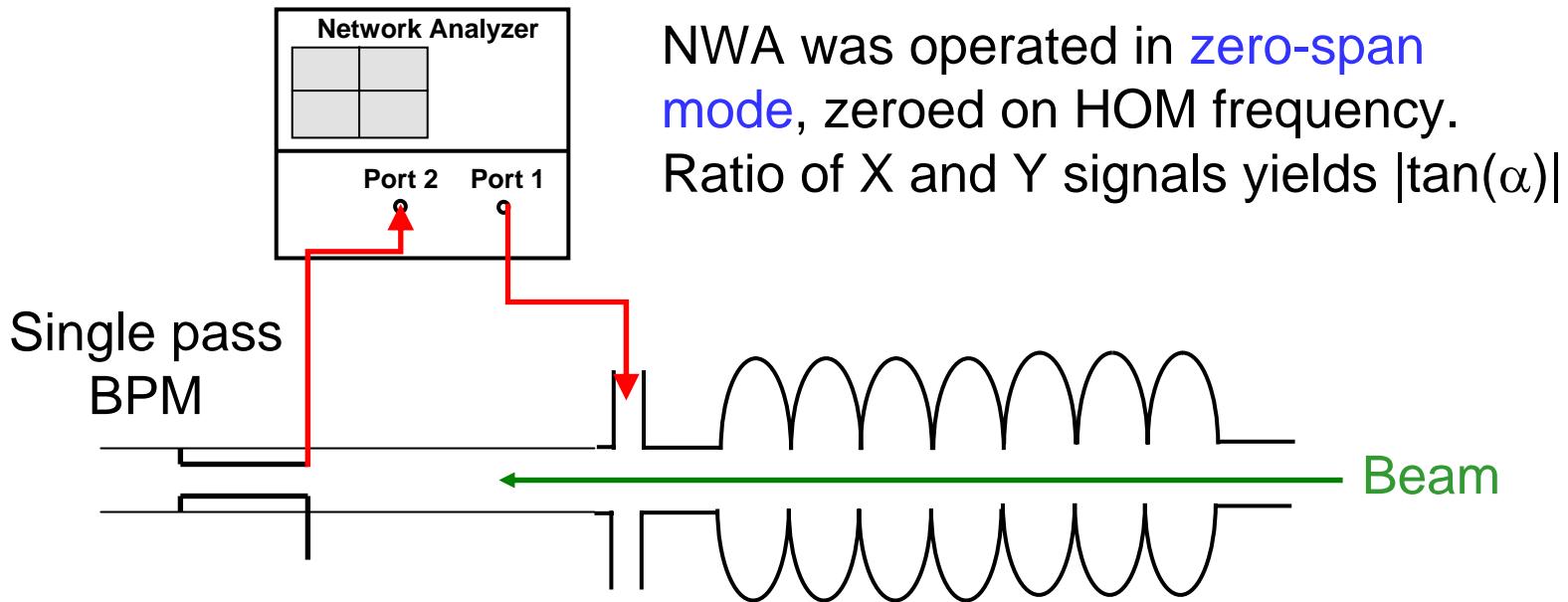
	Threshold increase factor	Considerations for Implementation
Electronic	Damping Circuit	5 <ul style="list-style-type: none">• Do not effect beam optics• Work for only for 1 or several modes per cavity• Long term stability of system can be an issue
	3-Stub Tuner	1.5* <ul style="list-style-type: none">• Can prevent reaching optimal optics setup required for a physics program
Optical	Phase Trombone	2-3 <ul style="list-style-type: none">• Can prevent reaching optimal optics setup required for a physics program
	Local-Reflector	5

* - has not been properly tested (long connection cables)

HOM polarization angle measurements

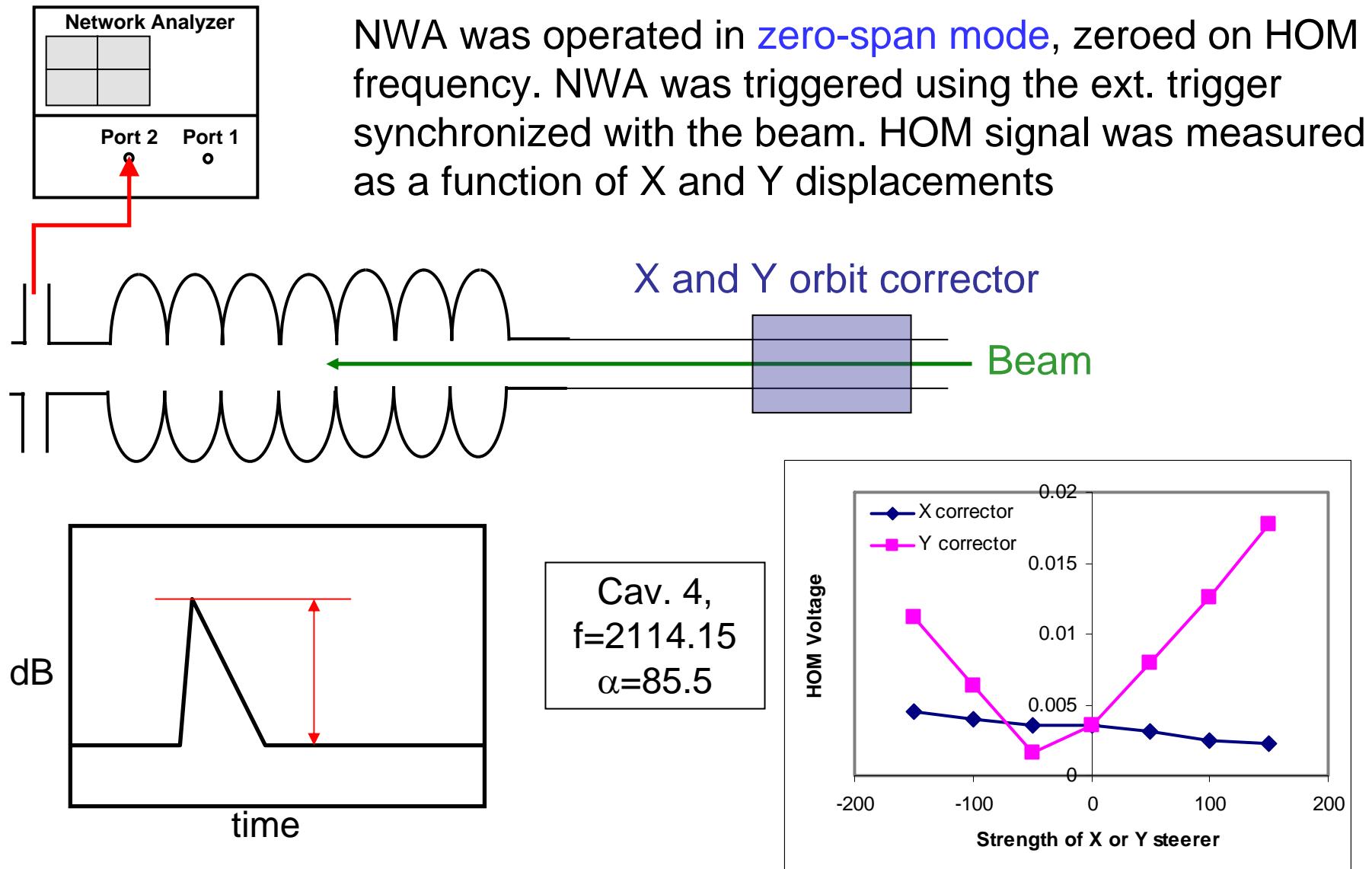
HOM polarization angle is an important parameter if a high accuracy of BBU simulations is required

HOM polarization angle measurements: Original Plan



MPS allowed to run only 250 μ sec-long, 2 Hz pulses

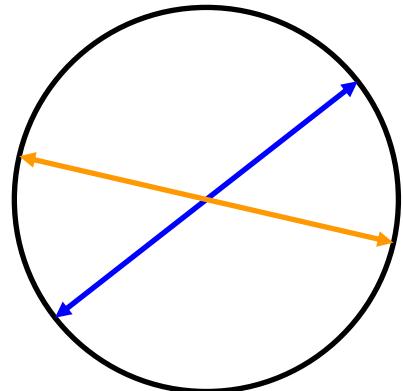
HOM polarization angle measurements: Plan X



HOM polarization angle measurements: Results

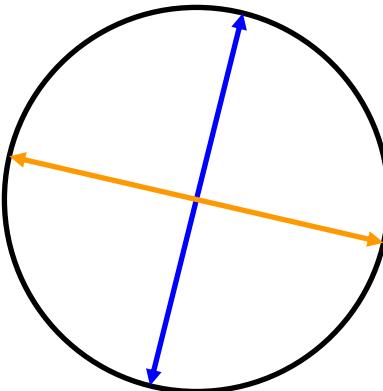
CAV. 3

$f=2104.2$
 $f=2104.4$



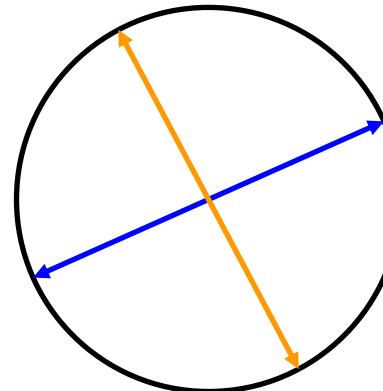
CAV. 3

$f=2115.39$
 $f=2115.68$



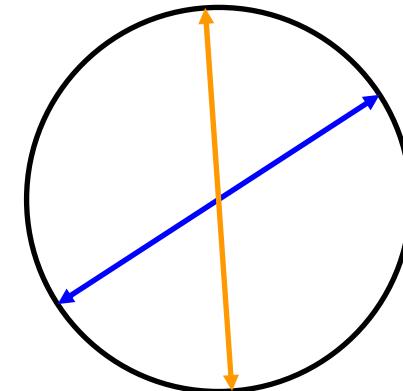
CAV. 4

$f=2102.54$
 $f=2102.64$



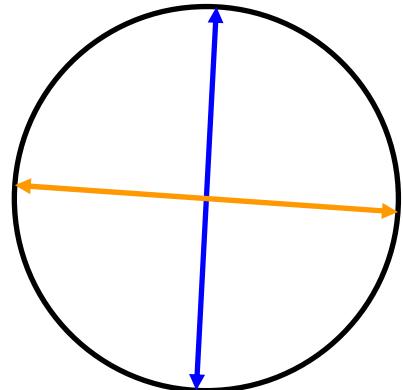
CAV. 4

$f=2114.0$
 $f=2114.16$



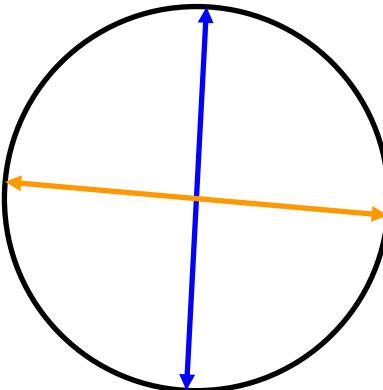
CAV. 7

$f=2106.0$
 $f=2106.7$



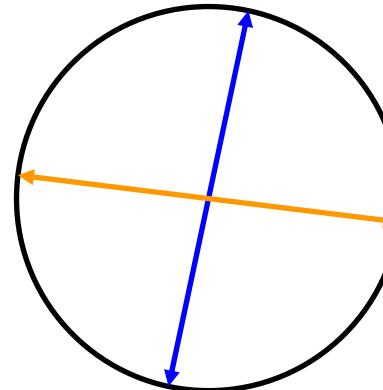
CAV. 7

$f=2116.58$
 $f=2117.23$



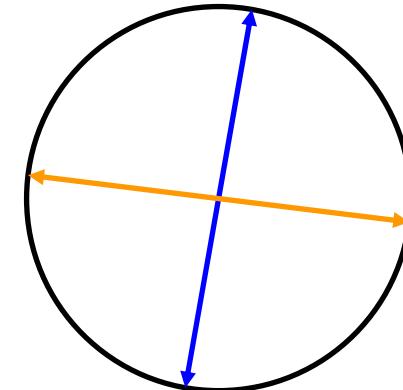
CAV. 8

$f=2102.59$
 $f=2103.0$



CAV. 8

$f=2113.15$
 $f=2114.15$

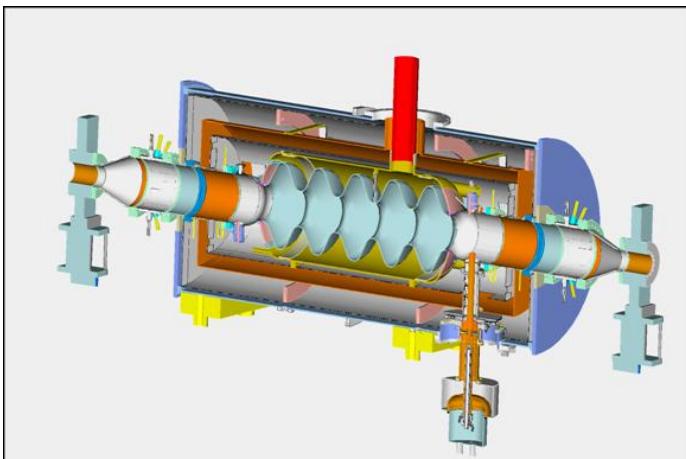


Multi-pass BBU suppression in perspective of large-size machines

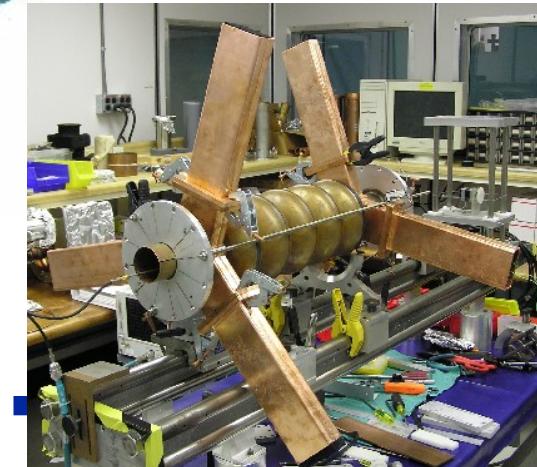
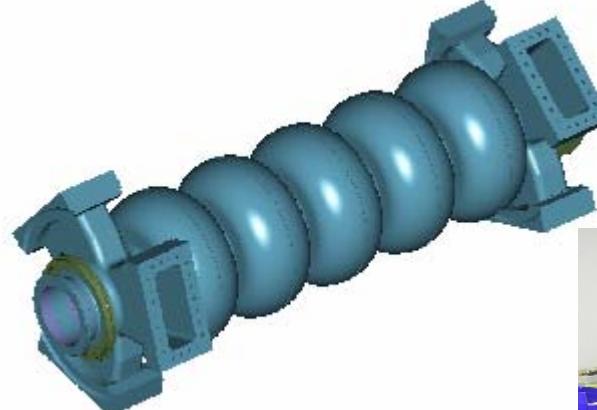
HOM damping

- Design of multi-cell cavities with low-Q, low-R/Q HOMs seems to be the most reliable way to increase the BBU threshold in large-scale ERLs
- The work is under way at BNL, JLAB, Cornell U...

BNL



JLAB



Cavity-2-Cavity HOM frequency spread

Cornell ERL

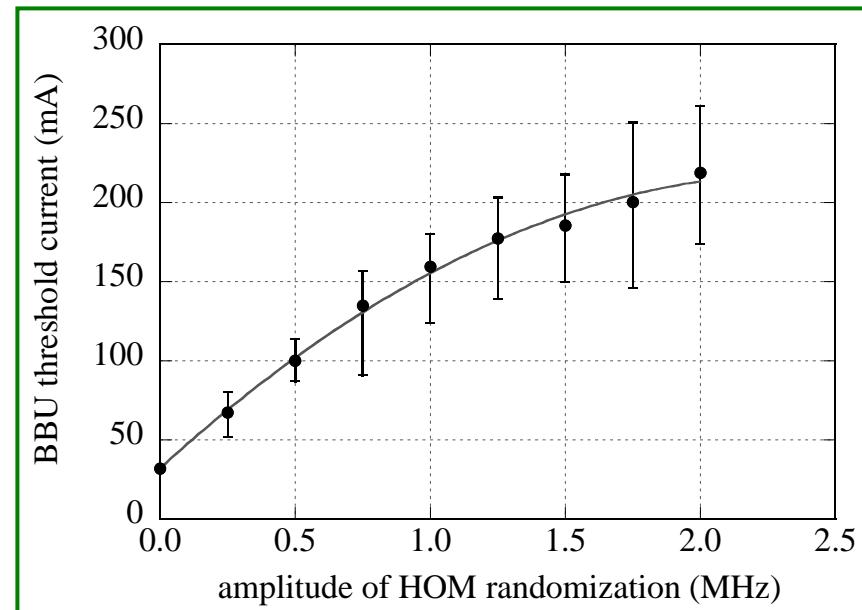
$Q=2.1E4$, $N_{\text{cav}}=320$

(Hoffstaetter, Bazarov, Song)

$\sigma_{f_{\text{HOM}}} (\text{MHz})$	$I_{\text{th}} (\text{mA})$
0	25.8
1.3	280
10	418

6-GeV JAERI ERL
Cav./HOM parameters - ?

(M. Sawamura, R. Hajima)



Optical Methods

- Optical methods become less efficient if the number of HOMs is large
- Optical methods might not work if the number of accelerating passes > 1
- For Cornell ERL, optical rotation of betatron planes increases the threshold by a factor of 3-5

	Coupling OFF	Coupling ON
σ_{f_HOM} (MHz)	I_{th} (mA)	I_{th} (mA)
0	25.8	103
1.3	280	867
10	418	2420

(Hoffstaetter, Bazarov, Song)

Broad band feedback

- Must restore bunch position on a single pass (assuming two-pass machine)
- Growth times of the order of a single recirculation
- Similar feedback systems have been used in rings
- A narrow band, slow feedback for each HOM is possible but not practical

Cumulative Beam Breakup

- Frequency spread
- Cavity alignment

Acknowledgements

- C. Tennant (JLab)
- L. Merminga, G. Krafft, B. Yunn (JLab)
- S. Benson , D. Douglas, K. Jordan, G. Neil, FEL team (JLab)
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- Todd Smith (Stanford)
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- Stefan Simrock (DESY)